IND TECHNOLOGY DEVELOPMENT PLAN – FY04

Communications Systems Analysis Work Area

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OBJECTIVE:

Develop innovative communication and information technologies to enable future missions at lower cost and with higher scientific returns. This effort is focused on improving space communication capability at low cost through research, analysis and development in key areas of channel coding, advanced digital signal processing, and overall communication system design.

GOALS and SIGNIFICANCE:

- Develop error-correcting coding and modulation schemes, and devise new communication strategies to maximize data return for future deep-space missions. This work area will continue to exert leadership across NASA in channel coding for deep-space and in-situ communications, and to provide accurate performance analysis of coding and modulation schemes, including implementation losses. It will develop new, higher performance or lower complexity systems, and influence code selections by CCSDS and other space agencies.
- Develop decoder architectures. Coding and decoding concepts will be demonstrated, and designs suitable for implementation with current technology at low cost and at higher data rates will be developed.
- Perform system analysis to characterize expected operational performance and evaluate technology alternatives for future deep space communications. Develop, maintain, and analyze data on new technologies (performance, costs, uncertainties, and risks) and potential future flight project needs in order to characterize the expected operational performance of future DSN systems, evaluate technology alternatives, and identify potential improvements. [This area is not funded in FY 04].
- Develop, validate and test efficient, adaptive combining algorithms for large antenna arrays consisting of up to 4000 elements. Develop new methods for uplinking using large arrays, eventually replacing current uplink methods on 70m antennas.
- Develop communication network methods suitable for deep space communications, towards the realization of the interplanetary network. Characterize the performance of the proposed protocols.
- Develop advanced telemetry receiver designs and algorithms for future high data rate missions at 100 Mbps and beyond [This area is not funded in FY 04].

The complexity and the cost of many present deep-space telemetry links are dominated by antenna size on the spacecraft and on the ground, by available power on the spacecraft, and by DSN operations costs. Future small missions will require very efficient communication systems. Information theory, error-correction coding, and advanced signal processing techniques can provide performance improvements at higher return-on-investment ratios than larger antennas or heavier, more powerful spacecraft. This is accomplished by pushing the communication channel closer to its theoretical capacity limits, while reducing computational complexity with respect to current methods and guaranteeing high reliability. Communication link efficiency is obtained by protecting the data with powerful error-correcting codes (channel coding), by using advanced modulation techniques that are both power and bandwidth efficient, and by using communication strategies that simplify DSN operations.

The planned development of large ground antenna arrays and the potential for nuclear powered spacecraft will require transponders, receivers and coding systems capable of much higher data rates than currently offered by existing DSN telecom subsystems. The high data rate thrust started in FY03 in this work area is an essential step in achieving high data rates from Mars and beyond. In FY04 the coding thrust will address high data rate coding systems for the Mars-Earth backbone link and in-situ coding systems, including on-board decoders. It will be later extended to the equally necessary development of high data rate ground receivers.

System analysis provides the technical foundation for tradeoffs involving costs, benefits, and risks associated with future DSN communication systems and new technologies (e.g., Ka-band can reduce mass by 20-30% and power by 30-45%, for Mars missions transmitting 1-10 Gbit/day). In order to achieve and demonstrate improvements in complex missions, careful system-level planning, link analysis, study of atmospheric data, and evaluation of technology alternatives for future DSN microwave and optical systems are needed. Particular emphasis is placed on

Ka-band technology, which has 4-6 dB link performance advantage over present X-band links. Weather effects at Ka-band will be mitigated by the use of powerful yet simple to decode erasure-correcting codes, to guarantee sufficient quality of service on weather-dependent channels. Since the DSN is evolving from a simple point-to-point communication system to the long-term goal of an interplanetary network, adaptive relay protocols will be developed and characterized to adapt to unpredictable environmental conditions and to provide services meeting data integrity constraints.

Large antenna arrays are being developed elsewhere for radio astronomy purposes and are planned for deep space telemetry applications by replacing and vastly outperforming the current 70-m DSN apertures. Novel combining and antenna signal processing algorithms suitable for very low SNR operation can enable efficient usage of such antenna resources in terms of multi-beam capability, interference rejection, robustness to outages, efficient uplink strategies, etc.

The net results of the methods considered in this work area are higher science returns at lower cost than by using alternative technologies, thus enabling lower cost missions. This work area also finds and demonstrates better uses of current telemetry systems and recommends changes. New designs and ideas are structured for timely transfer from this work area to DSN implementation. This has been and will continue to be useful to maximize the return of NASA's technology investments.

PRODUCTS:

- Low-complexity, high performance coding systems.
- Performance analysis of coded systems, including system losses.
- Codes for specific requirements: high code rate, bandwidth efficiency, emergency communications, very low BER ($<10^{-9}$), etc.
- Novel architectures for low-complexity decoder implementation at higher data rates, including belief propagation decoders.
- End-to-end system performance analysis aimed at characterizing the expected operational performance and evaluating technology alternatives for future deep space communications. ARQ and/or erasure correcting methods for weather dependent channels (especially at Ka-band).
- Protocols for deep space and in-situ communications, leading to the interplanetary network. Adaptive data rate systems, and associated performance characterization at both the link and relay network levels.
- Algorithms for large antenna array combining, including testing in realistic environment. Concepts for uplink arraying, including phase control strategies and cost/benefits comparisons with current uplink system.

INTERDEPENDENCIES:

Our work on low-complexity codes for high speed decoding and on bandwidth efficient coding is related to a parallel effort in GSFC. Coordination will maximize the joint benefits to NASA.

The Adaptive Relay Protocols task will be performed in collaboration with the Information Systems Protocol effort with same objective.

The Uplink Array and Large Array Signal Processing Testbed tasks will be periodically reviewed by the 940 Large Array task manager to monitor alignment with the overall goals.

Initial work on next-generation receivers for higher data rates is being considered in the 940 organization. Coordination of this effort with 970 is necessary, and preliminary analysis and requirements definition should be started before embarking in the implementation task.

RESOURCE REQUIREMENTS BY WORK UNIT

	JPL Account	*FY03*	*FY04*	*FY05*	*FY06*
High data rate comm. links - LDPC	102148 K.77.300.00.0001	300	500		
High data rate in-situ code – LDPC	102148 K.77.300.00.0002	0	250		
Adaptive relay protocols	102148 K.77.300.00.0003	0	150		
Guaranteed Quality of Signal on unpredictable channels	102148 K.77.300.00.0004	0	0		
Uplink Array	102148 K.77.300.00.0006	0	350		
Large Array Signal Processing Testbed	102148 K.77.300.00.0005	0	500		
Total		**300**	**1750**		

Description of Individual Tasks.

A1. Coding for High Data Rate Mars-Earth Link (T1)

This thrust will primarily benefit Mars missions requiring high data rates and will realize the end-to-end performance improvements made possible by large RF antenna arrays. The proposed coding system is a piece of the overall plan for a 100 times improvement of the DSN capabilities (e.g., from 1 to 100 Mbps from Mars). Alternatively, such improvements can be exploited for sustaining lower data rates with much lower transmitter power, including direct-to-Earth links.

Objective. The overall objective is to devise and demonstrate bandwidth efficient LDPC (low-density, parity-check) codes for the Mars-Earth link at ≥ 100 Mbps, including the design of high-speed decoders using FPGA technology. In FY 04 we will focus on defining a standard rate 1/2 LDPC code and on implementing a prototype decoder at 10 Mbps.

Significance. This is a key technology for 100 times improvement in data return from Mars in conjunction with higher spacecraft directional power and large RF antenna arrays. The proposed coding system is also being considered by the JIMO mission.

CCSDS standard turbo codes are the state-of-the-art for deep-space communication. These 16+16 state codes offer excellent power efficiency, providing coding gains in excess of 10 dB. On parallel DSP's, a data rate of approximately 700 kbps (scalable to about 1.6 Mbps with additional DSP's) is currently being achieved. MRO has requested this capability already, and future missions will likely require higher rates due to advances in ground antenna arrays and nuclear powered spacecraft. However, inherent structural complexity of turbo codes makes additional data rate improvements increasingly difficult. It would require banks of multiplexed turbo decoders, with increasing processing capability required on the interconnecting backplane. For very high data rates, a better solution to meet this thrust goals is to seek out codes that lend themselves to extremely low complexity decoders.

The entire concept of the Interplanetary Network (IPN) is predicated on the capability to handle high-speed, low-SNR data. We do not have that benefit now. Hence every mission that expects to use data rates above 1.6 Mbits/second (the projected eventual capability of the turbo decoder implementation currently underway) will depend upon results from this research.

Metrics. Code selection is driven by a large number of well-quantified measures — selecting an appropriate tradeoff between them is a harder matter. Threshold SNR is the single most quoted metric for an error correcting code, and in FY03, we developed tools that determine a code's threshold with high precision, and methods to design codes that perform excellently in this regard. The codeword and symbol error floor metrics can be determined by software simulation — we will improve our ability to measure and control this parameter through an FPGA implementation in FY04.

Decoder complexity is measured in edge evaluations per decoded bit, and is determined in the code design process. Encoder complexity is kept linear in block length, and small, by choosing codes with as many degree-1 and degree-2 variable nodes as check nodes. This permits using a generalization of the Irregular Repeat and Accumulate (IRA) or back-substitution encoders. Simplicity of code description is determined by the size of the protograph, and of the permutations used to "grow" the protograph seed into a full code description. JPL research is in the lead on the first factor, and research is ongoing in the development of expansion methods based on circulant matrices, hierarchical circulants, and other regular structures.

Return on Investment. Channel coding is a very low-cost method to reduce required transmit power. The primary ROI is in enabling high data rate missions. Expressed in dollars, we estimate a ROI of $12 million with the successful completion of the work in this task. This is based on an estimated $3 million for development and deployment in the DSN, versus approximately $15 million for development and deployment cost of achieving the same data rates with CCSDS turbo codes, which would require hundreds of custom-designed ASIC's in parallel.

No decoder currently exists that can handle data at 10 to 100 Mbits/second with SNR levels as low as are routinely encountered in the deep space environment. Several missions are being planned (MTO, JIMO, etc.) that will depend upon this capability.

Approach. Over the last two years, this work area has maintained a position at the forefront of research in LDPC code design. We have found families of LDPC codes that match or exceed the best known codes, many of which are proprietary, in any design criterion: threshold SNR, error floor, encoder complexity, decoder complexity, etc.. Research must now address the details necessary to bring this investment to fruition. This requires first resolving some remaining code design issues, such as simultaneously achieving a low error floor and simple code description for codes with small block length. These problems will be addressed by expanding our collection of tools for designing "protograph" based LDPC codes. One key step in the design process is to expand a protograph to a full LDPC code, which we currently do with the Progressive Edge Growth (PEG) algorithm. We will investigate alternative methods for lower complexity overall codes. These expansion methods will be based on circulants, hierarchical circulants, and constrained versions of PEG that avoid particular types of low-weight codewords and related graph structures.

Upon completion of this investigation, we will select a few codes for standardization that score well on each design parameter and achieve an appropriate trade-off between them. This will be a set of codes that cover a range of block lengths separated by powers of four, perhaps $k = 2^{10}$, 2^{12}, 2^{14}, and 2^{16} bits. We will initially focus on the development of a rate 1/2 code, chosen so that its extension to rate 3/4 will not alter its favorable performance and complexity characteristics.

Decoders for LPDC codes are inherently parallel, consisting of simple messages passed on an underlying bipartite graph, and they are ideally suited for implementation on a single FPGA. Hardware implementation of a decoder for our proposed code in an FPGA will demonstrate its capabilities and assist immeasurably in technology infusion. This will proceed from the proof-of-concept FPGA decoder implemented in FY03, which successfully demonstrated 30 Mbit/second decoding of regular LDPC codes, though with significant implementation losses in performance. We will begin by investigating quantized belief propagation decoding algorithms for irregular LDPC codes, using uniform and non-uniform quantizers in several representations (log-likelihood ratio, "unreliabilities", log-probability, etc.). From software simulation results, an appropriate algorithm will be selected for hardware implementation.

The decoder will include a carefully designed "stopping rule" for an optimum tradeoff of speed and performance, and a basic design for the high-speed frame synchronizer will be developed. Finally, we will make sure that the VHDL code is well documented and saved as a "core" to be used in the future for possible ASIC production.

We will also produce a standard FPGA implementation for the encoder, which will be re-usable by multiple missions. The encoder/decoder pair will be used for extensive testing. This may involve the procurement of a new FPGA board and of a larger (8M gates) FPGA. The demonstration of the decoder prototype will include a GUI to control the various parameters and to collect performance statistics.

We will perform an end-to-end systems analysis of the new code. With data rates approaching 100 Mbps, many aspects of the usual channel coding problem change noticeably. For example, implicit in a 100 Mbps data rate is the use of bandwidth efficient signaling. Therefore, we will concentrate on high rate codes (1/2 to 3/4), and analyze the performance in conjunction with bandwidth efficient modulations such as OQPSK.

Deliverables.

- Family (different code rates and block sizes) of LDPC codes selected and submitted to CCSDS for standardization. (Q1)
- IPN progress report describing the design and selection of these LDPC codes. (Q2)
- Quantized "belief propagation" decoding algorithm that achieves small quantization losses and permits high-speed implementation, documented by software simulations and a technical memo. (Q3)
- Performance and spectral efficiency of LDPC codes in conjunction with OQPSK modulation. (Q3)
- FPGA implementation of quantized belief propagation decoder prototype for the selected code. FPGA implementation of encoder. (Q4)
- Benchmarking of decoder speed and report on decoder performance. VHDL code "core" documentation. (Q4)

Infusion Plan. Prompt and successful infusion is the key motivation behind the work described here. Standardization of a selected set of codes is a lengthy process, but critical to successful transfer of technology to spacecraft missions and potentially also to the commercial applications. The FPGA implementation will serve to resolve remaining technical issues (quantization of the algorithm, efficient decoder architectures), and will even provide a prototype for following applications. Encoder design is a far simpler task, and we will make example software encoders available.

A2. High data rate in-situ code – LDPC (T1)

Objective. Design an LDPC (low-density, parity-check) code suitable for in-situ links and a space-qualifiable decoder for operation on-board the orbiter at speeds in excess of 4 Mbps. Analyze the performance of this coding system when used with ARQ techniques on bursty communication links.

Significance. The current JPL-designed radio for proximity links (Electra) is forced to used 30 year old coding technology due to availability of space qualified decoders only for convolutional and Reed-Solomon codes. Its performance can be improved by 2 dB or more by using state-of-the-art LDPC codes. In addition to this power efficiency advantage, LDPC codes offer flexible block sizes, which are particularly useful for ARQ applications.

The design of the code and decoder take advantage of extensive experience at JPL in this specific field and of a parallel effort on planet-to-Earth coding systems, described in another work unit in this work area. The use of iterative decoders which inherently produce reliabilities of the decoded symbols will also pave the way for integration of the decoder function within next generation software radios, as is being studied in a separate R&TD task.

The proposed coding system will improve Mars network communications and permit a unified strategy for surface data return. Since this design will be directly applicable to an improved Electra radio and to the future Electra-lite radio, it will produce substantial return on investment, which will be amortized over all future Mars network missions. This design will also reduce dependency on the only vendor of space-qualified coding ASICs.

Approach. We will first select an appropriate LDPC code for in-situ links, with near-optimum performance at relatively short block sizes, which are required in in-situ ARQ systems. This code will belong to the same family of LDPC codes considered in the companion task on planet-to-Earth coding systems.

The decoding complexity for the on-board decoder will be considerably lower than that required for the ground decoder, by exploiting the hierarchical structure of our protograph code designs, which allows for tradeoffs in the amounts of parallelism/seriality, so that a slower decoder can be built on a smaller FPGA, with lower parallelism. This in turn will allow us to use off the shelf rad-hard FPGAs, which typically provide a substantially lower number of gates than their non-rad-hard counterparts.

We will quantize the messages exchanged in the “belief propagation” decoder even further than in the ground LDPC decoder to minimize the decoder complexity, at small price in performance degradation, which will be quantified.

We will test the coding system with a simple ARQ scheme controlled by the LDPC decoder itself, and demonstrate its performance advantage over the current Proximity-1 protocol.

Finally, we will investigate extremely simple LDPC codes and decoders for applications such as the envisioned Electra-lite radio and DS2-like radios. We will report on the tradeoff between performance and complexity/speed.

Deliverables.

- Selection of LDPC code for in-situ links, and performance evaluation. (Q2)
- Design of decoder structure with limited parallelism based on protographs. Results on performance/speed tradeoff with different choices of quantizers. Methods to extract error detection signal for ARQ, based on symbol reliabilities. (Q3)
- Implementation of decoder in rad-hard FPGA. Characterization of performance and comparison to present Electra coding system. Benchmarking of speed. (Q4)
- Characterization of coding system performance with simple ARQ scheme, and optimization of block size. (Q4)

A3. Adaptive relay protocols (T14).

Objective. Develop an integrated, common protocol set for deep space relay communications that adapts to environmental conditions and provides services meeting data integrity constraints. Adaptive data rate mechanisms, automatic repeat request (ARQ) techniques, and distributed buffer resource management capabilities will be developed, and performance benefits quantified through simulation and analysis. The focus of this task in FY 04 is the development of adaptive data rate methods, particularly for proximity links (i.e. links between assets within the same planetary region), such as will occur for MRO and MTO relay operations.

Significance. Use of relays has proven benefits across many missions, enabling stressed asset (e.g., probe) a wider operational regime and lower cost. This thrust will substantially advance relay communications efficiency and improve science return volume and quality. An increase of 5dB of in-situ transfer volume is expected.

It is recognized that very substantial benefits arise from the use of relay assets by both lowering mission costs and enhancing the science information that is collected. Provision of relay capabilities allows assets within the planetary region to reduce their own need for costly interplanetary communications resources, with high bandwidth communications satisfied by proximity links to the relay orbiter. Relay resources made available to regional assets also include storage facilities, permitting smaller buffers that may be cleared more frequently to make room for further science data. In addition, many more communications opportunities with human users are made available, resulting in much faster turnaround times between scientists and the remote assets. The faster responsiveness will allow many more controlled operations to take place, yielding several times the scientific information otherwise derived.

Relay systems have long been utilized, and their capabilities have evolved over time. Basic low-layer protocols and services, coupled with sequence command files that drive their operation, have been defined and successfully implemented. However, major improvements are apparent and arise from the application of adaptive techniques that dynamically accommodate unpredictable events and conditions. Channel performance (e.g., received signal strength) can vary significantly from estimates made from prior analyses, and in the past these have been mitigated by simply applying a large enough link margin to guarantee that these stochastic deviations stay above a minimal threshold needed to close the link. In proximity ("planetary area network") communications, application of in-situ monitoring of the link quality and rapid autonomous adaptation of the data rate, coding and modulation permits reliable operation with much smaller link margins, thereby achieving substantial cost-effective improvements in total data transport capacity. Emerging use of Ka band and optical communications for interplanetary links promises high bandwidth, but these media are subject to significant degradation and outage arising from weather over Earth ground stations. Although limited by the ability to predict weather and the long propagation delays of interplanetary scale links, adaptation of the remote transmissions can be accomplished and provide significant performance enhancements. In addition to variation at the physical layer, future missions will employ an increasing degree of operations autonomy. In turn, this will cause greater unpredictability in the demand for communications services. The relay communications protocol suite to be developed in this task will provide the flexibility to accommodate such mission dynamics, while adapting to physical link variations, to maximize the efficiency and cost-effectiveness of the overall IPN relay network.

Justification and Benefits. Use of adaptive techniques is rapidly growing in wireless communications systems, with recent standardization of such methods in such applications as 3G commercial mobile communications promising ubiquitous application in the near future. This technology can provide substantial increases in bandwidth, and also enables unequal error protection necessary to achieve the appropriate quality of service for each data stream type. Leveraging this technology for space exploration missions will provide a low-cost method to significantly expand the total volume of returned data.

Metrics. A key metric on the adaptive data rate technology of this task is total volume of returned data. An additional metric is the variance of the volume of data over specified time intervals; this measurement is important due to the nature of the targeted new technology, which promise much higher total data volumes but can result in unpredictable variation in short-term transfer rates. Further metrics are the latency in transporting data from source to destination, as well as the rate of data that is lost. Another target technology will provide unequal error protection to different data types, and therefore each of the metrics indicated above will generally depend on data type classification.

It is expected that as much as three times increase in data volume will be achieved through use of adaptive data rate techniques on proximity links. The increase for use of rate adaptation on interplanetary links is not expected to be as large (due to large lag in the control loop), but still quite significant. Data return variance will be larger for systems with rate adaptation, however, because the total bandwidths are larger, the latencies are expected to be lower. Different data types will have different latency requirements and therefore use of differentiated services is expected to significantly improve those metrics. By properly weighting individual metrics across the data types, we expect to see substantial improvement in overall data loss rates.

Return on Investment. Increased Throughput. Currently, in-situ links are highly under-utilized because they are operated using conservative link margins based on predicts derived without knowledge of actual conditions. By developing new technology to allow operating adaptively through active link probing and dynamic in-situ parameter adjustments, the total volume of bits returned can be dramatically increased. This would yield a 1.3 dB increase if constrained to x 2 data rate step (2.8 dB if also steering the orbiter antenna); 1.6 dB increase if x root 2 data rate steps are used (3.3 dB if also steering the orbiter antenna). ["Mars Relay Variable Data Rate Study," J. Breen & D. Bell, July 2002].

Gains from using ARQ for reliable link control are estimated as follows: 2.9 dB increase if the link margin is relaxed 3dB and 5.6 dB increase if the link margin is relaxed 6 dB. One can conclude that a 5 dB increase of in-situ link efficiency is achievable with use of adaptive link control protocol that combines ARQ and dynamic data rate. ["Mars Relay Link Margin and Error Control Protocol Study," Gao, Clare & Jennings, July 2002].

Approach. A major component of this task will investigate the data rate adaptation for proximity links. Key issues to be addressed are:

- Full duplex vs. half duplex and associated ability to provide channel quality feedback.
- Interface with the coding layer, including the need for synchronization between data rate change events and code block delimitation, as well as mechanisms for interleaver and convolutional coding processes in conjunction with discrete data rate changes.
- Data rate adaptation decision process, including whether the source transmitter makes autonomous decisions or the receiving node commands data rate changes.
- Methods for deriving the current channel quality, such as received signal strength, bit error rate metric from decoder chip, or MAC CRC frame error rate (or ARQ NAK rate). Characterization of the accuracy of each of these methods, and the latency generated and impact on control loop operation.
- Data rate change indication techniques and performance impact. Data rate changes decided by the source transmitter may be conveyed via interspersed "header" data transmitted at low rate (such as is used in IEEE 802.16); an alternative method is issuance of an explicit "directive" message (such as used in the CCSDS Proximity-1 standard).
- Performance effects of the granularity of data rate change increment (e.g., Electra data rate changes occur at 2X increments), as well as the temporal granularity (minimum inter-event duration) at which data rate changes may be made (e.g., every frame).
- Differentiated services, in which unequal error protection is provided across different data types. For example, time-critical information may be transmitted at a lower data rate, which has a higher link margin that essentially guarantees error-free delivery in a single transmission attempt (no retransmissions needed). (This technique will also be applicable to the interplanetary case, where it is likely to have a greater impact.)
- Technology infusion assessment regarding incorporation within existing CCSDS standards as well as implementation implications.

The results of this investigation will be compiled into an IND Progress Report.

Additional effort will be directed toward characterization of the end-to-end performance impacts of the use of adaptive data rate on either or both links (proximity and interplanetary) in a multi-hop relay network. This effort will be based on development of simulation models that will be integrated into our existing simulation tool suite that includes a QualNet-based discrete event simulation engine. Initial effort will develop the adaptive data rate model for the interplanetary link, such as will occur between MTO and Earth/DSN. Link level analyses will be conducted and performance characterized parametrically (control loop lag, channel variation, predictability of the channel conditions, etc.). Subsequent effort will extend the model to the proximity link case, in which alternative methods for data rate adaptation will be constructed. Characterization of the different proximity link methods will be determined through simulation studies. Finally, we will develop end-to-end models and analyses. Comparisons will be made between (1) the nominal use of highly predictable (essentially guaranteed) albeit relatively low data rate performance based on large link margins and no adaptation, vs. (2) use of adaptive data rate methods. Thus quantification of the benefits of rate adaptation, and the operational impacts of such use, will be determined.

Deliverables.

- Demonstration of simulation of adaptive data rate interplanetary communications (Q2).
- IND Progress Report on adaptive data rate techniques for proximity communications (Q3)
- Demonstration of simulation of relay network performance and characterization of adaptive data rate methods on proximity and interplanetary links (total data volume and variability) (Q4)

A4. Guaranteed Quality of Signal on unpredictable channels (T3)

[Task canceled 10/24/03]

A5. Uplink Array (T23)

Objective. To develop new methods for uplinking, using multiple radiating elements to enhance existing DSMS assets and to enable the implementation of uplinking on the proposed array of small antennas. These higher performance solutions are enabling improved uplink capabilities that are likely to be needed as deep-space mission requirements expand, and the existing large apertures age.

Goals & Significance.

Goals:

1. Study and report on the relative cost/performance comparison of three uplink solutions, 1) large apertures (single or array of few), 2) array of 12-meter apertures (10-100), 3) use of flat array (fixed). Recommend near and long-term development.
2. Study the components of the existing range of apertures for uplink arraying. Determine accurate array related performance of existing assets. In many cases, there is significance array specific information that is missing.
3. Develop an end-to-end error budget for the uplink array components; from predict to spacecraft. Identify the performance parameters that accurately represent the sub-systems within the array. Identify the needed accuracy of parameters; develop the associated metrology.
4. Develop an operational concept for uplink array with existing assets. Focus on (identify) enabling methods for testing/calibration and on operational performance verification methods. Identify needed accuracy and metrology for both calibration and operational scenario. Validate measurement methods on existing assets.
5. Develop the calibration method using radar technique. Identify all calibration steps (assume phase-stable ground equipment). Identify set of parameters that that are sufficient to verify correct operation of array, i.e. coherency at the spacecraft (return signal level, ephemeris accuracy, antenna location, etc.). Identify required accuracy in needed measurements, both for operational and calibration. Identify metrology that will return required accuracy, and verify.

Significance:

Currently, DSMS can only use 20 KW radiated power at X-band on the 70-m aperture. At S-band the power level is 400 KW. Significant increase in S/C received power could be achieved if uplink arraying is made operational for dealing with S/C emergencies or when the 70-m antenna is not available for extended periods. More importantly, the long-term plans replace the existing large apertures with a large array of smaller apertures (~12-m antennas). It is vital that accurate performance requirements are placed on the new antennas for uplink, a direct (future) result of this technology task. In addition 920 has shown a need for increased command rates for future missions due to richer science goals.

Products.

The task will deliver several study papers:

1. Cost/performance comparison between large appertures/12-m antenna/flat plate array solution
2. Block diagram of large aperture array and error contribution by each existing component.
3. End-to-end error budget with error sensitivity information, parameter lists for verification and metrological methods.
4. Methods to achieve phase-stable ground system. Describe local and global loop controls.
5. Radar technique for uplink array calibration (parameters returned, accuracy, and method of verification).
6. Answer the question of practicability of uplink arrays with existing or near future technologies.

Description.

The task will proceed on three parallel paths.

1. Study of uplink array solutions. Potential contributors are Hurd/Bagri/333, and external (920 study) for flat array (80K). Evaluation of the existing apertures and the cost effectiveness of uplinking on the large array of small antennas will be done by the team. For information on the suitability of the flat-plate

array we will draw on the study currently under way by 920. The resulting paper will provide the cost/performance comparison between large appertures/12-m antenna/flat plate array solution.

2. Study of existing assets and development of error budget. Definition of phase-control loops. Work by 331/Hurd/Bagri and mostly 333. (150K). This component is the key to proceed forward with an uplink array development. Once we have an accurate error model for the major blocks of the uplink chain such chain can be procured or designed.
   a. Develop an end-to-end block diagram and establish error sensitivity for each block. Key person is F. Amoozegar to pull together the information.
   b. Fill in each block with measured performance information, using existing DSN components as starting block. Evaluate performance in respect to uplink array needs. Generate spreadsheet models for testing and validation
   c. Work with local and external experts to improve the 'block' performance where necessary.
   d. Define an end-to-end control mechanism that produces a phase stability as good as or better than currently available for receive arraying. Highlight is on the antenna phase center stability model.
   e. Produce a definitive report on the end-to-end error budget requirements for a successful uplink array and a solid evaluation of the existing assets' suitability for such array work.
3. Radar calibration method will be done by University of Michigan (80K). The radar methods should complement the available calibration methods. The study will establish the potential accuracy of the radar methods and where they could replace more expensive calibration techniques.
4. Complete a paper on the practicality of the uplink array approach in the near term and further in the future. Identify significant error contributors and a viable solution for error containment.

Deliverables.

1. Cost/performance comparison of three solutions to uplink array (Q2)
2. End-to-end error budget and metrology (Q2, Q4)
3. Evaluation of existing assets (Q2, Q4)
4. Phase-control strategy for large aperture array (Q3)
5. Summary paper on uplink arraying (Q4)

A6. Large Array Signal Processing Testbed (T2)

Objective: Develop a COTS-based simulation testbed for cost-effective evaluation, testing and validation of Large Antenna Array systems performance, operational concepts and signal-processing techniques.

Significance: The testbed will permit early detection of possible design problems in the 100-element Large Array Prototype. That prototype presents new challenges in signal processing and high-rate telemetry under weak-SNR conditions that must be thoroughly understood.

Approach. The Large Array Testbed (LAT) will be used primarily to evaluate the performance of candidate algorithms designed to optimally combine the array outputs under precisely simulated conditions closely resembling real-world DSN operations. The LAT employs a combination of high-speed analog and digital hardware, and conventional computer software to create, propagate, down-convert, and process a vector of digital data-streams under conditions closely resembling true array operation in the field, but at a small fraction of the cost, complexity and implementation time required even for a small prototype array.

JPL is developing the technology for very large RF antenna arrays, with up to a thousand or more individual antenna elements. These large arrays will ultimately replace the largest monolithic parabolic reflectors now in use for receiving data from distant spacecraft to Earth. JPL is also planning to develop smaller arrays to upgrade in-situ communications from UHF to X-band. The signal processing necessary for combining the signals of each antenna element of the array can be based on well-established correlation methods or on more modern adaptive, closed-loop methods that determine the optimum combining weights adaptively and with minimal computational complexity.

With single DSN antennas, the usual operational scenario involves dedicating one antenna to one spacecraft at any given time. With a large array of antennas it is possible to form several narrow independent beams, enabling simultaneous reception of more than one spacecraft signal. With the high data-rates planned for future missions, the modulated carriers may overlap and hence cannot be easily separated by filtering the IF spectrum. While this situation can often be mitigated by the use of conventional interference suppression techniques that effectively place a null in the direction of the unwanted spacecraft, this approach can become ineffective when multiple spacecraft orbiting the same planet appear along the same line-of-sight. These situations represent realistic spacecraft configurations in future deep space missions that will certainly pose significant signal processing challenges to the large array. Therefore, it is important to understand and evaluate array performance under a wide range of operating conditions, including the simultaneous reception of signals from multiple spacecraft received in the presence of planetary interference and time-varying tropospheric effects.

A conceptual block diagram of the LAT is shown in Fig. 1. The inputs to the LAT are modulated RF carriers generated by one or more spacecraft transponders: as an example, these inputs could be generated by the "small deep-space transponder" (SDST) assemblies, as shown in the figure. The baseline LAT design calls for a single spacecraft input, however this will be expanded to dual inputs in the future to simulate multiple received signals. The signals from the SDST are down-converted to IF, sampled at the Nyquist rate, and serve as input to the Digital Signal Processing Assembly (DSPA) comprised of FPGA cards and associated support electronics. There are four distinct functions carried out by the DSPA: first, digital combining of IF samples if multiple inputs are used; second, down-converting the combined IF samples to complex baseband; third, distributing the IF samples to N parallel channels (where N is the number of antennas simulated); and fourth, imprinting the simulated time-varying channel conditions on each complex symbol-stream. The output of the DSPA is a pair of N-component complex vectors of "realistic" samples that serve as input to a signal-processing computer where the Combining Algorithms are applied and the Combiner (or beamforming) operations are carried out.

The user interface to the DSPA is provided via a LabView "graphic user interface" or GUI. The GUI resides on a computer that can be used to input parameters, thus enabling the user to define various channel models of interest, such as the timescale of variations due to spacecraft and ground clock drift, tropospheric phase variations induced by the motion of humid cells across the array (either clear-air moisture or clouds); covariance of correlated noise from planetary background, and independent noise variance contributed by each receiver front-end; and time-varying relative delays caused by the combination of earth-rotation and array geometry.

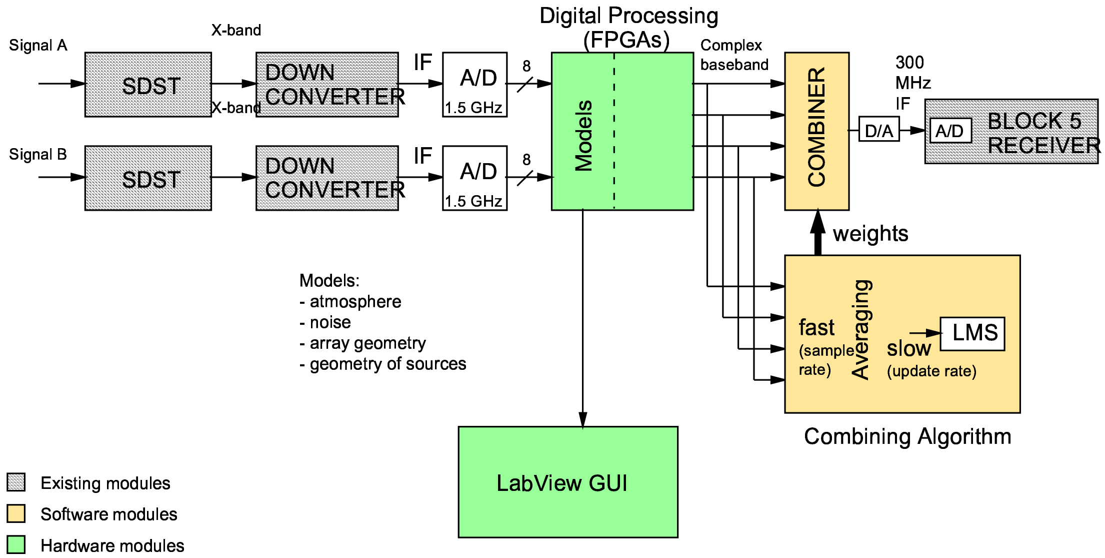

Figure 1. Conceptual block diagram of Large Array Testbed: Green blocks represent hardware components, tan blocks software components. Shaded blocks are auxiliary equipment supplied by the user or equipment common to the lab.

The "realistic" sample-streams generated by the DSPA and simulating real-world effects are used by the combining algorithms to estimate the optimum combining weights and delays needed to minimize the BER of the detected and decoded data. This operation may involve estimation of signal, interference, and noise covariance matrices used by conventional "correlation-based" algorithms that obtain the optimum weights either as the largest eigenvalue of a covariance matrix, or if separate signal estimates are also available, as the product of covariance inverse and conjugate of signal vector. These algorithms are extremely inefficient, typically "order N^3" in complexity, and hence computationally intensive for large arrays: however, they serve as useful baselines to compare the performance of highly efficient modern "gradient descent" algorithms such as the LMS and CMA. These algorithms do not estimate the covariance matrix directly to determine the optimum combining weights, relying instead on estimates of the gradient towards the optimum weight-vector solution in an N-dimensional "weight-space". Their complexity is linear with the number of array elements, and these algorithms are known to converge to the optimum weights under nominal operating conditions. Investigating their performance under adverse conditions that include single spacecraft near a bright planetary background, multiple spacecraft orbiting the same planet and thus creating mutual interference in addition to the background, and a combination of these scenarios occurring in the presence of time-varying tropospheric delay variations and instrument instabilities, is the primary goal of the Large Array Testbed development effort.

Deliverables.

A simulation testbed, complete with user-manual, for high-confidence evaluation of complex scenarios, including detection and tracking techniques, before deployment of the array.

Specifically:

- Develop basic h/w, s/w architecture based on specific cots components (Q1)
- (In parallel) Investigate and specify all array channel model impairments, time scales, dynamic range, dynamic behavior, fixed point models, etc. (Q1 and Q2)
- Begin working/implementing some of those models in order of priority -- probably array geometry first -- how to perform narrowband & wideband time delays in the h/w models (Q2 and Q4)
- (In parallel) Develop (or adapt existing) combining algorithms and integrate in testbed. (Q2 and Q4)
- Develop GUI (Q4)